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Determination of Actual Forces on Bridge Piers Due to Moving Ice

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C. R. Neill, ***Hydraulic Engineer, Research Council of Alberta.***

Introduction

In a paper presented at the 1965 CGRA convention, A. B. Sanderson[1] discussed ice forces on bridge piers in general terms. Drawing on a number of Canadian, American and Russian references, he outlined the physical properties of ice, current design standards for ice pressure, and the various modes of pressure that can act on piers. He concluded: "It seems idle to speculate on what ice forces are, and it is high time competent investigators set out to find out empirically what in fact is the magnitude of these forces."

With a view to reinforcing Sanderson's arguments for further consideration of the question, the aim of the present paper is to discuss the maximum forces probably withstood in the past by some old bridges in Alberta, and to illustrate two methods of measuring dynamic ice forces by means of specially instrumented piers situated in a large and in a small river. The field observations made in 1967, at the Athabasca River bridge, which are summarized herein, have already been described in greater detail in a limited distribution report.[2] The test pier has also been described in a short news article published in the United States.[3]

Is the Design Code Too Conservative ?

Questions About the Present Design Code

Both the AASHO and CSA codes used on this continent for the design of highway bridges state simply:

> "All piers and other portions of structures which are subject to the force of flowing water, floating ice, or drift shall be designed to resist the maximum stresses induced thereby. The pressure of ice on piers shall be calculated at 400 pounds per square inch. The thickness of the ice and the height at which it applies shall be determined by investigation at the site of the structure."

In applying the code to the design of a pier, the maximum height that the ice will act can usually be determined fairly closely. Evaluation of the other factors, however, is more difficult. What ice thickness should be used in the calculation of the force, and is 400 psi indeed the proper crushing strength under the conditions found in nature ? Such things as the shape, width, slope, and mass of a pier and the character of the river itself are also likely to affect the actual force exerted by the ice.

Many specialists have reported that the physical properties of ice are extremely complex, even under controlled conditions, its test strength varying from 80 to 1,800 psi depending on several factors. Considering the even greater complexities of ice under natural river conditions of formation and decay and all the other mentioned variables, it seems impossible to believe that all these factors analyzed separately could be so correlated as to reliably predict the ice force that actually occurs on a given pier. Probably the only way to find out what these forces really

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are is to measure them on objects which are as similar as possible to bridge piers. In the meantime, however, examination of old bridges that were built to a lesser standard than the present code allows, some of which have failed and some of which have withstood the test of time, may provide valuable information.

Examples of Ice Action On Old Bridges

Many older bridge piers in Alberta that were not designed according to the present code have been taken out by ice, and spectacular damage has also occurred to other parts of bridges. This damage, as well as the witnessing of severe ice runs in larger rivers, has tended to make designers wary about reducing design values for ice pressure below the 400 psi suggested by the code.

A review of bridge histories on the Pembina River (which has flood flows of up to 40,000 cfs and is subject to heavy ice runs) reveals that, of 16 road bridges built on it, since 1917, seven were taken out by ice. Most of these bridges, including the seven that failed, had timber piers consisting of three rows of piles covered with planking and filled with stones. It isn't possible to calculate the total strength of this kind of pier, but this was not a factor in their destruction. Reports describe that they were chewed away piece by piece. Some piers, however, survived ice runs even though the timbers were in a fairly rotted condition and, before they failed, the upstream portions were missing.

Figure 1 shows the Flatbush Bridge on the Pembina, which was taken out by ice two days before its completion. Like the other bridges, the piers were of hollow timber construction but they had not yet been filled with rock. The inspection report of the failure describes a sudden rush of "huge chunks of ice 3-feet thick" which in a short time tore the sheeting off the pier and then cut out the piling one by one. It is significant that the piers did not fail as a unit. A calculation of the probable resistance of even half the pier which survived a severe buffeting for a time suggests that the gross ice pressure had not exceeded more than about one-quarter of the equivalent code value.

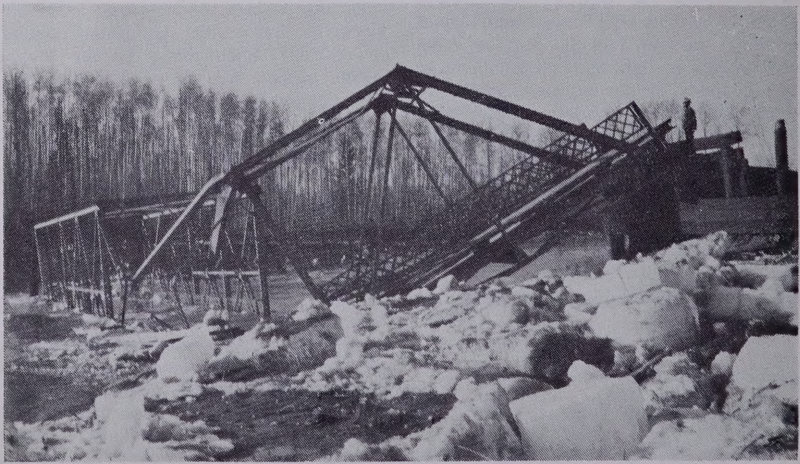


Figure 1 — Destruction of bridge at Flatbush on the Pembina River. (Timber piers were taken out by ice in 1956.)

On the Red Deer River (about twice the size of the Pembina), of a total of 17 road bridges built since 1896, eight were destroyed by ice. As in the cases on the Pembina, the piers were of timber construction and they failed in the same way. A different type of failure is illustrated by **Figure 2,** which shows the remains of a 1,500-foot long railway bridge on this river destroyed by ice in 1952. This bridge was supported on high steel towers resting on concrete pedestals. The failure resulted when ice jammed to a level above the concrete pedestals and pushed the towers off. Spectacular though all these failures are, they do not necessarily support the severity of the present design code. They do, however, serve to classify these rivers as having severe ice conditions.

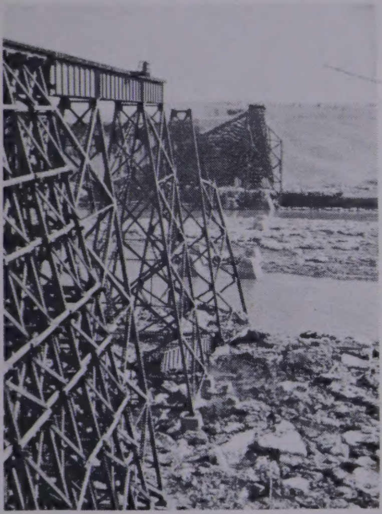


Figure 2 — Destruction of bridge over the Red Deer River. (Taken out by ice in 1952.)

Figure 3 shows the Content Bridge on the Red Deer River built in 1906. Although ice destroyed the trusses in 1928 and has damaged the bottom chord on three occasions, the piers survived all the ice runs that destroyed the other nine bridges. The concrete in the three piers (which has no reinforcement) is of poor durability, of low strength, and has no appreciable tensile bond between the various pour levels. An analysis of the pier shaft itself indicates that it would have fractured at streambed level if the code equivalent of the ice pressure had in fact exceeded 120 psi based on ice 3 feet thick. A check analysis of the stability of the entire pier indicates that it should have overturned if the ice pressure had exceeded 180 psi; that is, less than one-half the value specified by the code.

The concrete piers of the Bindloss Bridge, built in 1922, further downstream and of similar construction, also show no signs of movement although the steel trusses were damaged by ice. A 1946 report indicates that, after the ice run, ice 6 feet thick was lying across the flood plain for a width of 1,500 feet. An analysis of the piers indicates that they should have overturned if an equivalent code pressure of 240 psi had been exceeded with an ice thickness of only 3 feet.

Similar analysis of old concrete piers in the Bow, Ghost, and Little Smoky Rivers indicate that the equivalent code values of ice pressure to fail the piers would be 150, 250 and 190 psi respectively. It seems reasonable to conclude that the actual ice forces have been less than these amounts.

There are also several smaller rivers in Alberta that put up substantial ice runs. Many old bridges with timber piers on those rivers have withstood flows of ice reported to be up to 3 feet thick. Although in many cases the timber had reached a state of considerable rot, the piers — in contrast to those in the larger rivers — have not been in distress. This suggests that the smaller rivers warrant even lesser design values for ice pressure than do the larger ones.

Although both the information and its analysis briefly described above are crude by research standards, they do

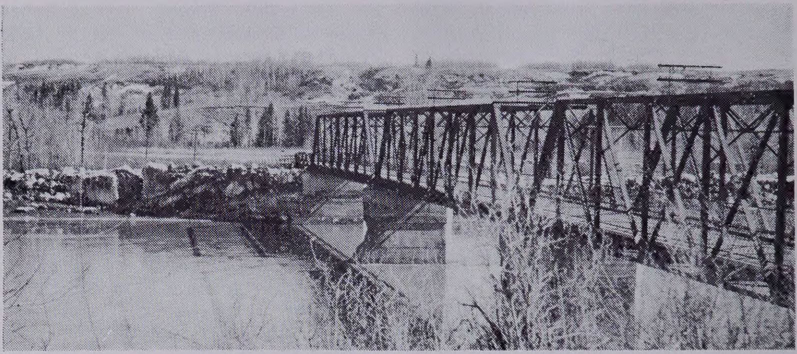


Figure 3 a — Bridge at Content over the Red Deer River. Built in 1906.

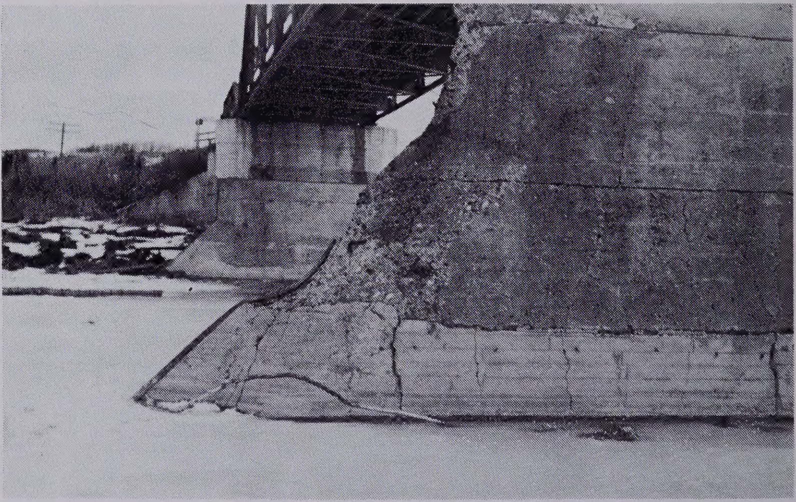


Figure 3 b — Old concrete pier of Content Bridge.

suggest that actual maximum ice pressures, at least in the rivers examined, are considerably less than the present code specifies. The fact remains that until more definite information is collected for the various kinds of rivers, there is uncertainty as to what degree the design code is conservative. There is little alternative but to design for ice forces in the manner prescribed by the code unless, on the basis of experience, judgment and personal conviction, an engineer is willing to accept responsibility for departing from the code. This is in fact being done in some cases.

Economic Advantages of Reducing the Code Requirements for Ice Pressure

Ice forces on a structure calculated on the basis of the code in many cases affect not only the cost of a bridge but also such items as the choice of span lengths, type of design, kind of pier, and the method and time of construction. Two examples are given below :

Figure 4 shows a bridge on the Battle River which, although a small river, is nevertheless subject to ice runs in the spring. The solid piers of reinforced concrete are typical of the type needed to withstand ice pressure on the basis of the design code. At present-day highly competitive prices, the piers cost $15,000 each. **Figure 5** shows a bridge on the same river but with piers constructed from steel piling. They are designed to withstand one-quarter the ice pressure prescribed by the code, were built in mid-winter, required half the time to construct, and cost $9,000 each. The concrete piers for a two-lane bridge in a large river (the North Saskatchewan), designed in accordance with the present code, cost 20 per cent more than those designed to withstand half that ice pressure. This amounts to a difference of about $80,000 or 10 per cent of the total cost of such a bridge.

A reduction of ice pressure by the amounts indicated above, or savings of the magnitude mentioned, would not necessarily be realized for all river bridges. However, if the savings are even half that amount, and extended to some 500 new rural bridges that will be required in the next few decades in Alberta alone, the savings still amount to several million dollars. Such potential savings justify considerable effort to find out what ice forces actually are and to refine criteria for pier design. It was for all these reasons that a study of the problem was included in the Alberta Co-operative Highway Research Program in 1962, leading to the development of two field installations for measuring ice pressure.

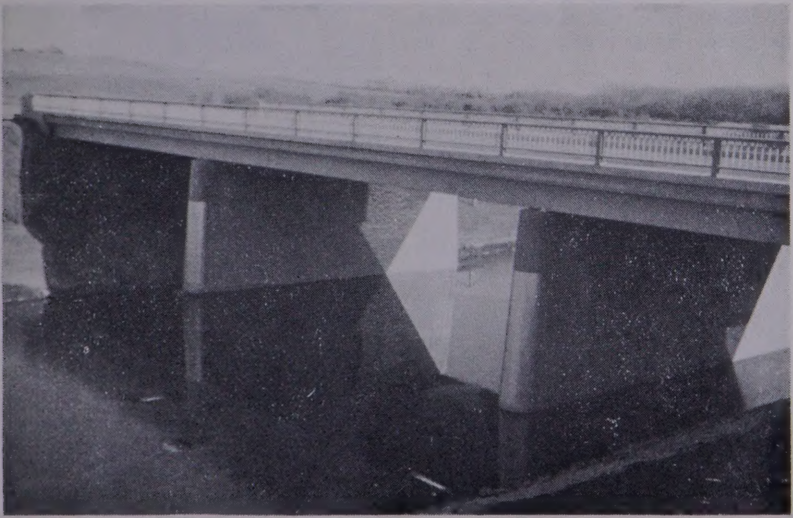


Figure 4 — Bridge on Battle River with solid piers.

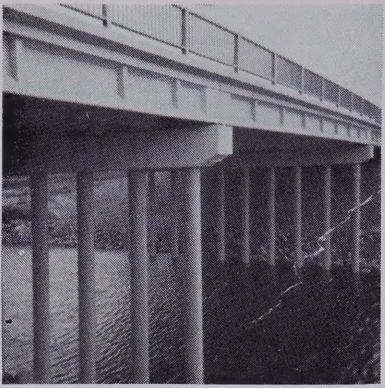


Figure 5 — Bridge on Battle River with pipe-pile piers.

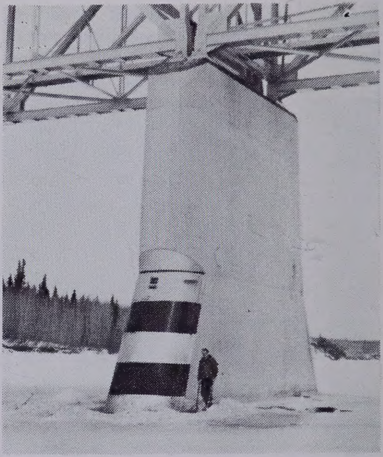
Load-Measuring Installations in Alberta

Installation at Hondo Bridge

A special nose section designed to permit recording of a dynamic ice loading was incorporated, during construction in 1965, in one of the piers of a highway bridge of five 200-foot spans crossing the Athabasca River about 120 miles north of Edmonton. The location was chosen because this river, which can put up a flood flow of 200,000 cfs, has severe ice runs, and the bridge was yet to be constructed. **Figure 6** shows an aerial view of the bridge, and **Figure 7** shows the load-measuring pier.

Figure 6 — Aerial view of Hondo Bridge, Athabasca River, looking downstream. Load-measuring pier is the third from the left.

Figure 8 shows some details of the load-measuring pier. A section of the pier nose, consisting of a 22-foot long concrete-filled steel frame, is hinged at a point approximately 7 feet below low water level, and supported near its top by a steel cylinder fitted with resistance strain gauges. The cylinder or load cell is contained in a chamber within the body of the pier, reached by a manhole extending to the pier top. Provision is made for jacking the nose free of any ice frozen between it and the pier, and for replacing load cells. The strain gauge circuit is connected to an oscillographic recorder, which gives a chart record of the reactions on the load cells as ice strikes the pier. By observing the level at which the ice force acts, its magnitude can then be calculated by taking moments about the hinge. In measurements made so far it has been assumed that the ice forces acted horizontally at river water level. The water level is measured by means of a float-type clockwork stage recorder installed in a vertical gauging well in the centre of the pier.



Figue 7 — Load-measuring pier, Hondo Bridge. Painted stripes, 3 feet high, enable ice level to be read from photographs.

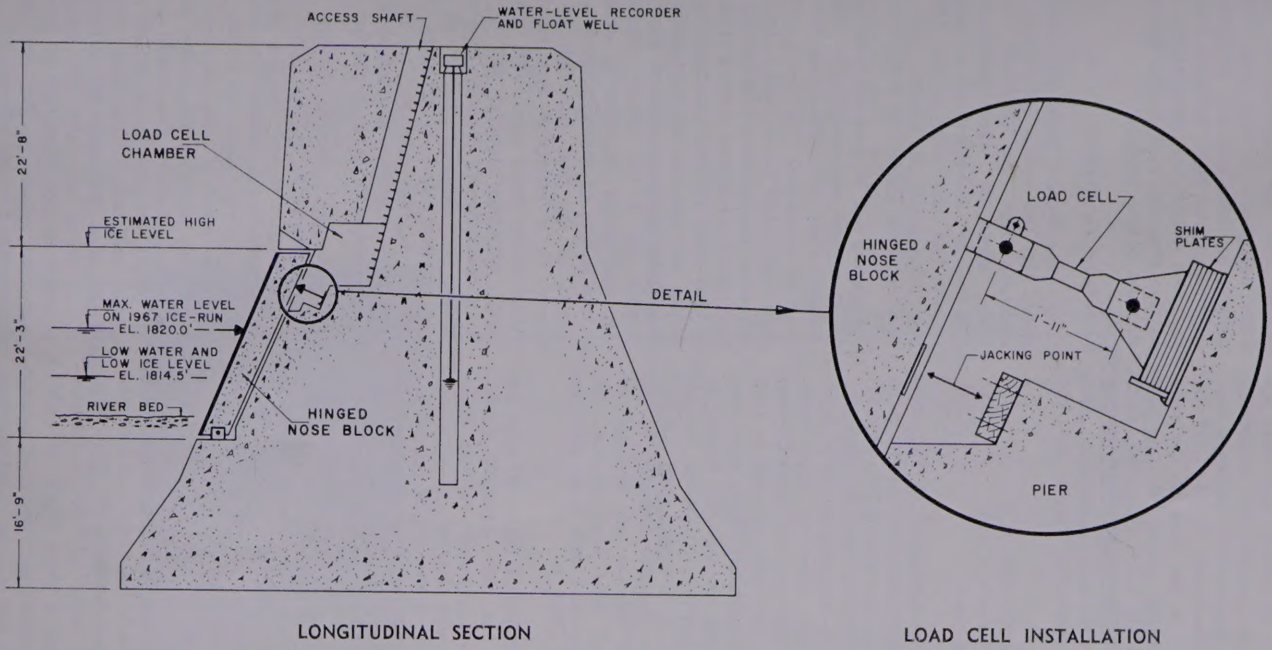


Figure 8 — Detail of special pier for measuring ice forces. Based on Alberta Department of Highways, Bridge Branch, drawings no. 4069 and 4073.

It should be noted that the arrangement is capable of measuring longitudinal forces only. Sideways movement is restrained by the stiffness of the hinge at the base of the nose and by parallel guides at the top. At the site of this bridge the river channel is fairly straight and parallel for some distance upstream, and substantial transverse forces are not expected.

Operating Experience with Hondo Installation

Laboratory calibration of the load cells and static load tests on site were done during the winter of 1966-67. The installation was then operated during the spring break-up period in April of 1967, and again in April 1968. Load measurements of interest were obtained in 1967 only, because in 1968 the river flows during April were very small and the ice virtually melted in place. In general, the device worked fairly well, although some minor difficulty has been encountered in the form of a variation of "drifting" of the indicated dead load reaction, apparently associated with some form of temperature effect.

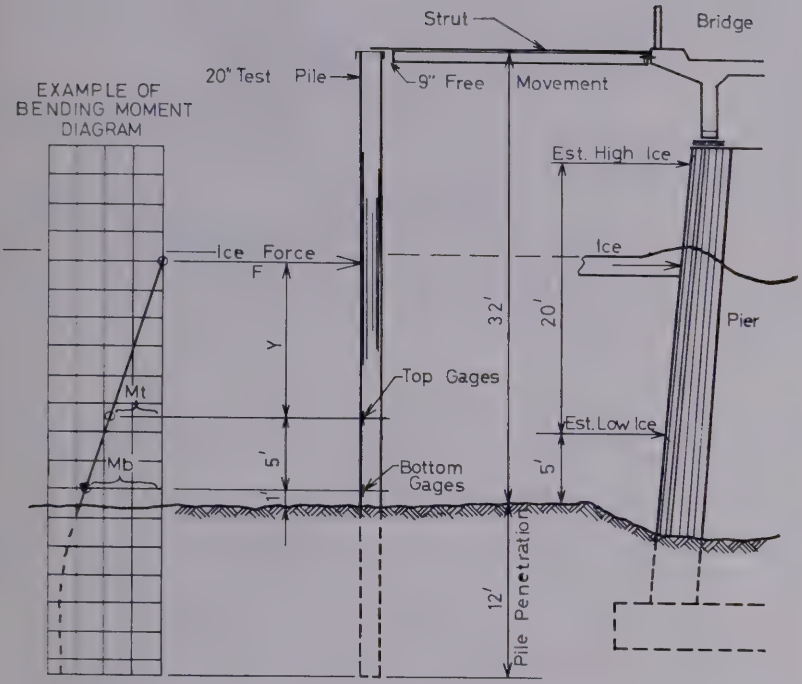
Supporting equipment used with the installation has been arranged as follows: The oscillographic recorder (Sanborn 321) was housed in a heated trailer parked at the end of the bridge, powered by a portable generator and connected to the load cell by 600 feet of cable. A one-frame-per-second pulse camera using 16 mm film was mounted on the bridge rail to view the pier nose from above, and was synchronized with the recorder chart to mark the film at specified intervals. In 1968 two standard movie cameras were also set on the river bank, one for general views and the other for close-ups of the pier nose. Floodlights (in case of night break-up) were mounted on the bridge structure. In 1967, when the only ice action of much significance occured, only a short length of usable film was obtained as a result of camera troubles. Better footage was obtained in 1968, but the associated ice forces were negligible. It has been found difficult to determine the thickness of ice striking the pier. Reliance has so far been placed on photographs and on measurements through the upstream ice-sheet before break-up.

Installation on Kneehills Creek

An experimental pipe pile was installed in the spring of 1968, just upstream from the Kneehills Creek bridge some 50 miles northeast of Calgary, to determine if a simpler system than that used at the Hondo installation would be feasible, and also to measure ice forces in a small river.

Figures 9 and **10** show the installation, which consists essentially of a 20-inch diameter steel pipe pile driven 12 feet into the streambed. It has a double thick wall (0.562 inches) and is designed to resist ice 2 feet thick acting 12 feet above streambed with a pressure of 100 psi. Electric resistance strain gauges are mounted at two points on the inside upstream wall of the pipe 1 foot and 6 feet above streambed. An oscillograph recorder is attached to the gauges to measure the bending strains in the pipe pile due to ice forces. It is estimated that ice flow in the spring could occur with a water depth anywhere from 5 to 25 feet. As a precautionary measure to prevent damage or complete failure of the pile, a steel strut is provided from the top of the pile to the bridge, and allows the pile to deflect freely a maximum of 9 inches at the top.

The bending moment in the pile can be determined at two points from the strains measured by the gauges. By extrapolating a straight line passing through the two points of known moment the point of zero moment can be found; that is, the point where the load is applied. This would permit the continuous recorder to be left unattended, and the readings later reduced should give not only the magnitude of ice force, but also the elevation at which it acts. The kind of bending that takes place in the pile below the streambed is not relevant.



Ice Force $F = \frac{Mt}{Y} = \frac{Mb}{Y+5}$

Also $Y = \frac{5Mt}{Mb-Mt}$

Moments Mt and Mb are calculated directly from gage reading.

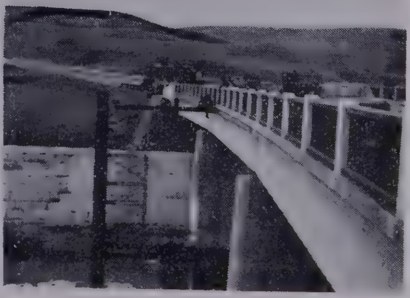


Figure 9 — Ice Load Recorder in Kneehills Creek.

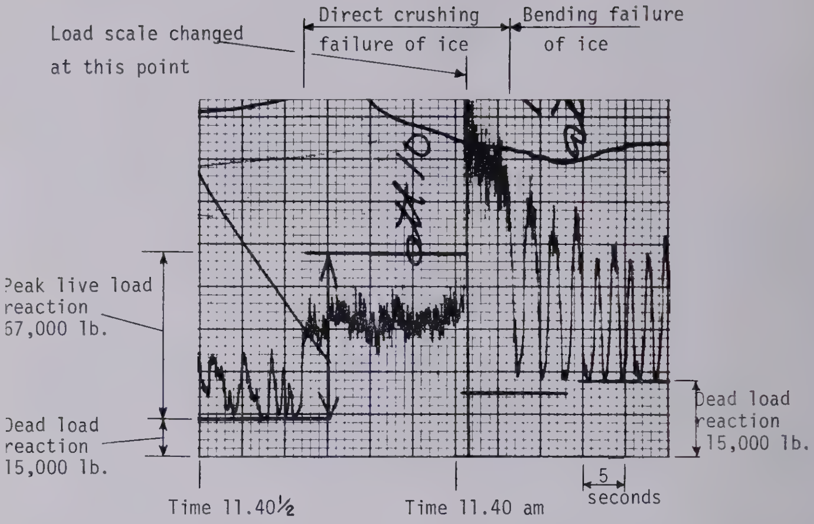


Figure 10 — Section of oscillographic chart from record of 30 April 1967 at Hondo Bridge, showing typical ice load oscillations. Note the two distinctive modes of oscillation.

Unfortunately, no ice run has yet occured against the test pile and the performance of this type of ice load recorder has not yet been proved.

Results of 1967 Ice Force Measurements at Hondo Bridge

On April 28, 1967, a more or less continuous ice-sheet that had extended several miles upstream began moving past the bridge. The piers cut through the sheet, leaving clean-cut open channels behind. Ice movement continued for nearly one hour, then the sheet jammed a short distance upstream of the bridge. Movement resumed the following day and continued for approximately half an hour, after which the river was practically clear of ice. The velocity of the ice-sheet near the piers was approximately 2 feet/sec. **Table I** gives a schedule of events for the two-day break-up period, and lists some of the highest ice forces as calculated from the oscillographic charts and water stage recorder.

The maximum ice force developed **(Table I)** was calculated as 141,000 pounds at ice-sheet level, corresponding to 20,000 pounds per foot width of pier. Assuming an average ice thickness of 15 inches, as estimated from photographs and prior measurements, the corresponding peak pressure is calculated as approximately 100 psi. These figures are based on the peak instantaneous reading of the chart. Because of force oscillations, mean values averaged over periods of a few seconds would be somewhat smaller.

Figure 10 reproduces a section of the chart recorded during a period of fairly high loading and covering 55 seconds in time. The oscillating nature of the indicated forces is typical of the entire record. Two dominant modes of oscillation are indicated. The first is characterized by a more or less regular oscillation from zero to full live load, with a period of 2 or more seconds : this mode seemed to be associated with an intermittent uplift and bending failure of the edge of the ice-sheet against the inclined nose of the pier.

TABLE 1

Schedule of events and associated ice-load indications during 1967 break-up period at Hondo Bridge

Date and time	State of river	Nature of chart recordings	Calculated peak (instantaneous) ice force on 7-ft. wide pier — lbs.
28 April	Continuous static ice-sheet up-river. No ice in contact with piers. Partial ice-sheet down-river. Small pieces breaking off sheets. Water elevation 1815.5 ft.	Dead load reaction only.	—
29 April 2:10 p.m.	Water elevation 1816.7. Ice-sheet began moving past bridge.	Irregular cyclic live loading, period approx. 5 secs., troughs reaching zero.	58,000
2:28 p.m.	Piers cutting through sheet.	Regular cyclic loading, period approx. 10 secs.	
2:58 p.m.	Ice-sheet jammed between river banks few hundred feet upstream of bridge. No further movement until 30 April. Piers free of ice.		
30 April 11:25 a.m.	Water elevation 1819.2. Ice-sheet resumed movement past bridge.	Irregular, generally small ice forces.	
11:27 a.m.			49,000
11:40 a.m.	Apparently hard white ice striking pier. Water elevation 1819.6.	Cyclic loading, period 2 secs., followed by steadier load vibrating at several cycles per second in which troughs do not approach zero.	106,000
11:43 a.m.			
11:50 a.m.	Soft ice passing special pier. Harder ice occasionally striking adjacent pier.	Loads low.	—
11:52 a.m.	Hard white ice striking pier. Water elevation 1819.8.	Vibrations, several cycles per second, troughs not approaching zero.	88,000
11:54 a.m.	Severe crushing and splitting of ice-sheet around pier.	High-frequency vibrations alternating with irregular lower-frequency oscillations.	136,000
11:55 a.m.	Water elevation 1820.1. Collar of broken ice around pier nose extending to 4-5 ft. above sheet level.	High-frequency vibrations (several cycles per second).	141,000
11:56 a.m.		End of significant live load.	
12:01 p.m.	End of ice-sheet. Thereafter small isolated floes only.		

The second mode, which occurred during all the highest load periods, is characterized by small-amplitude vibrations, at a frequency of 4 or more cycles per second, superimposed on a relatively steady and substantial base load : this mode seemed to be associated with direct crushing failure of harder or thicker ice which was slowed down as it crushed against the pier, as was shown by pulse photography. Such a failure is illustrated in **Figure 11.** Both frequencies are believed to be determined by the failure processes and not to be related to the natural frequency of vibration of the pier nose and load cell as a mechanical system, which is estimated to be in the order of 100 cycles per second.

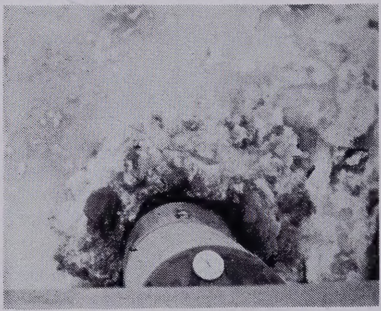


Figure 11 — View from above of hard ice crushing against Hondo pier, 30 April 1967. Clock correlates photograph with oscillographic chart.

The question of force oscillations is of more than academic interest. It is obvious that in the case of a massive pier the foundation need not be designed to withstand peak forces of extremely short duration. In the case of a flexible structure the separate consideration of resonance arises.

Other Dynamic Ice Force Measurements on Piers

The authors are not aware of any previous field measurements of the kind described having been made in Canada. Attempts at force measurements on a pier in the Dnieper River at Kiev, U.S.S.R., were described by Gamayunov[4] in two articles published in 1947. The device used was comparatively crude, consisting of a structural steel shield strapped to the outside of the pier nose. The reaction was taken by up to 28 hydraulic cells, all connected by manifold to an indicating manometer. During an ice-run in 1946, when ice 12 to 16 inches thick passed through the bridge at a velocity of approximately 3 feet/sec., the maximum force indicated was approximately 6,300 pounds per foot width of pier, corresponding to a pressure of less than 40 psi. The author admitted, however, that this was not a true reading because of the elasticity of the load-transmitting system. No mention was made of load vibrations.

Force measurements resulting from the action of sea ice on a 3-foot diameter cylindrical steel pile erected in Cook Inlet, Alaska, have been reported by Peyton.[5] Illustrations were shown of recorded force oscillations somewhat comparable with those reported herein, and interesting observations were made concerning modes of failure and structural response to force vibrations. Peyton noted that the highest loads occurred under what he called "ratcheting failure", when the ice was moving slowly or was virtually stopped. Typical frequency of oscillation was approximately one cycle per second. Because of the very different physical properties of sea ice and fresh water ice, the results are not necessarily applicable to river piers.

A large-scale experimental pier designed to obtain further data on sea-ice forces is being devised by the Department of Highways of the State of Alaska.

Conclusions and Recommendations

1. There are strong indications that current code requirements for ice pressure are unnecessarily severe for a high proportion of river bridges. The saving that would ensue from a reduction in specified ice forces justi-

fies considerable effort by many organizations to determine actual forces on bridge piers by a variety of methods.

2. One simple way to estimate an upper limit to actual ice forces is to evaluate the resistance of structures that have stood the test of time. The more of such analyses that can be made and compared, the more reliable would be the conclusions.

3. The ice force measurements so far recorded on the Hondo pier cannot be assumed to represent maximum or even average conditions. Measurements will be required over a period of several years, or at least until an obviously severe ice run is experienced. However, the results have demonstrated that it is practical, at reasonable cost, to determine the total dynamic forces developed even on a large pier structure.

4. The field investigations in the Athabasca River and in Kneehills Creek, in Alberta, were made possible only through the support of the Government of Alberta and through the joint facilities and staff of the Department of Highways, the Research Council of Alberta, and the University of Alberta, working closely on the project under the Co-operative Highway Research Program. The authors venture to suggest that CGRA might encourage a co-ordinated effort to further related investigations throughout Canada.

References

Reference No. 1 contains a list of some of the most significant publications up to 1964. Nos. 1 to 5 inclusive are items referred to in the text of this paper. The remaining items consist of significant publications and conferences post-dating 1964.

The first document produced as a result of the Alberta investigations was a short literature report issued in 1963. The substance of this report was later contained in an introductory statement on research problems pertaining to bridge piers and similar structures, included in reference No. 8.

1) Sanderson, A. B., *Ice forces on bridge piers.* Proceedings, 1965 Convention, CGRA, p. 147-157.

2) Neill, C. R., B. P. Shields, and others, *Ice pressure measurements at Hondo bridge, Spring 1967.* Mimeographed report, Alberta Joint Highway Research Program, August 1967.

3) "Pier measures ice pressures", *Engineering News-Record,* 14 December, 1967, p. 34.

4) Gamayunov, A. I., "Determination of ice pressure on bridge piers", and "Field measurement of ice-pressure on bridge piers". Two articles in *Tekhnika Zheleznykh Dorog* (Railway Technology), nos. 4 and 12, 1947. Translated by G. Belkov (NRC) and edited by C. R. Neill, 1965.

5) Peyton, H. R., "Sea ice strength". Contract report, Geophysical Institute of University of Alaska, December 1966.

6) Pounder, E. R., *The physics of ice.* Pergamon Press, 1965, 150 p.

7) McClure, G. S. and G. J. Herman, *A study of ice formations and their effect on bridges.* Mimeographed report, Montana State Highway Commission and U.S. Bureau of Public Roads, April 1965.

8) National Research Council. Conference on ice pressure against structures. Quebec, 1966; proceedings to be published 1968.

9) Seminar on Ice, 19th Annual Technical Meeting, Petroleum Society of C.I.M., Calgary, May 1968. To be published as special report 1969.

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